

Discussion on the entransy expressions of the thermodynamic laws and their applications



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ABSTRACT

In this paper, the entransy expressions of the three thermodynamic laws are discussed. The entransy expression of the first law is that the entransy of any thermodynamic system is in balance. For the second law, the entransy expression for heat transfer is that the entransy flow will never be transported from a low temperature body to a high temperature body automatically and entransy dissipation always exists. The entransy expression for heat-work conversion is that it is impossible for any device to operate in a cycle that receives heat entransy flow from a single reservoir and results in an equivalent amount of work entransy flow. The two entransy expressions of the second law are proved to be equivalent to each other. For the third law, its entransy expression is that it is impossible to achieve the zero entransy for any body through limited processes. With these expressions, the Clausius inequality is proved, and the concept of entransy loss is defined. The application of entransy loss to heat transfer and heat-work conversion is discussed.

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1. Introduction

Heat can be transported for heating or cooling bodies and doing work, which correspond to heat transfer and heat-work conversion, respectively. At present, the energy construction of the world is facing the rigorous situation, so the optimization of heat transfer and heat-work conversion is receiving more and more attention because it can increase the energy utilization efficiency in many engineering fields. For instance, thermal radiation can be optimized to increase the heat transfer rate as much as possible [1]. For heat-work conversion processes with heat exchanger groups, the distribution of the thermal conductance can be optimized to increase the output work [2]. For the optimization of heat transfer and heat-work conversion, some theories are developed to analyze the energy exchange processes [1–6], such as the entropy generation minimization [5], the entransy theory [6], etc.

From the viewpoint of thermodynamics, entropy generation always exists in practical irreversible heat transfer and heat-work conversion processes, and can be used to describe the irreversibility of the processes. Therefore, minimizing the entropy generation of the processes can decrease the irreversibility. With this consideration, researchers have done much work on the analyses

and optimizations of heat transfer and heat work conversion [4,5,7–14]. For instance, Ahmadi et al. [9] optimized a cross-flow plate fin heat exchanger with the entropy generation minimization method. Myat et al. [14] found that the minimization of entropy generation in absorption cycle leads to the maximization of the COP (coefficient of performance) in their analysis of an absorption chiller. However, there were some reports that showed inconsistencies between the entropy generation minimization and the optimizations of heat transfer and heat-work conversion [5,10,15–19]. The entropy generation paradox was noted in the analyses of the balanced counter flow heat exchangers, which shows that the heat exchanger effectiveness does not always increase with decreasing entropy generation number [5]. The heat exchanger effectiveness can be the maximum, an intermediate value or the minimum at the maximum entropy generation for different kinds of heat exchangers [10]. It was also found that minimizing the entropy generation rate of the refrigeration systems does not always result in the same design as maximizing the system performance unless the refrigeration capacity is fixed [16].

In recent years, a new theory based on the concept of entransy has been developed for heat transfer optimization [6]. The concept, entransy, was proposed by the analogy between heat and electrical conductions [6]. Heat flow corresponds to electrical current, thermal resistance to electrical resistance, temperature to electric voltage, and heat capacity to capacitance. Therefore, entransy was actually defined as the potential energy of the heat stored in a body,

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corresponding to the electrical energy in a capacitor. With this new concept, Cheng et al. [20,21] proved that the entransy will decrease during the heat transfer process in an isolated system, developed a microscopic expression of entransy for a monatomic ideal gas system, related the entransy to the microstate number, and indicated the microscopic physical meaning of entransy to some extent. In heat transfer, it was proved that entransy dissipation will always occur, and the concept of entransy dissipation could be used to describe the irreversibility of heat transfer [6,20,22,23]. Moreover, in heat conduction, heat convection and thermal radiation, the concepts of entransy, entransy flux and entransy dissipation could all be derived based on the energy balance equations [1,6]. Based on the concept of entransy and entransy dissipation, Guo et al. [6] derived the EEDP (extremum entransy dissipation principle) and the MTRP (minimum thermal resistance principle), and applied them to the analyses and optimizations of heat transfer processes.

In heat conduction, the entransy theory is found to be an effective theory to decrease the average temperature of the heated domain for the Volume-to-Point problem [6]. For the problem, a Lagrange function is formed based on the EEDP with the limitation of finite high conductivity material. By pursuing the extreme value of this Lagrange function, a rule of uniform distribution of temperature gradient is obtained mathematically. By putting the high conductivity materials at the place where the temperature gradient is high, the construct of high conductivity materials can be formed and the average temperature of the volume is reduced effectively. Moreover, Chen et al. [25] compared the entransy theory with the entropy generation minimization method. They found that the entransy theory results in lower average temperature of the volume than the minimum principle of entropy generation. Some other researches also indicate that the entransy theory is applicable for heat conduction optimization [26–29].

In heat convection, Guo et al. [6] and Chen et al. [30] developed the corresponding EEDP and MTRP with the energy balance equation, and derived the Euler equation that the flow field of the optimized heat transfer should satisfy based on the principles by mathematical derivation. The principles were found to be applicable to improve convective heat transfer [6,23,30,31]. Moreover, in laminar convective heat transfer, Wu et al. [31] found that the optimization results of the entransy theory lead to higher heat transfer rate than those of the minimum principle of entropy generation. Furthermore, the entransy theory was extended to optimize thermal radiation and analyze heat exchangers, and proved to be applicable [1,32–40]. When the entransy theory was used to analyze heat exchangers, there is no such paradox like the “entropy generation paradox” [34,37–40].

The entransy theory has been extended to analyze and optimize heat-work conversion processes [17–19,41–43]. Guo and Huai [43] applied the entransy theory to analyze and optimize the Iso-propanol–Acetone–Hydrogen chemical heat pump system. Cheng et al. [17–19,41] proposed the concept of entransy loss, which is the sum of the entransy dissipation due to the irreversible heat transfer and the entransy variation due to the work doing processes (i.e. work entransy). Entransy loss is the entransy change during the heat-work conversion processes. In the analyses of the irreversible Brayton cycle [17], the air standard cycle [18], the one-stream heat exchanger networks [19], the endoreversible Carnot cycle [41] and the Stirling cycles [42], it was found that the concept of entransy loss can be used to describe the change in the output power from the systems. The increase in entransy loss rate is in accordance with the increase in output power.

From above discussion, we can see that entransy is a new concept developed in recent years. Entransy dissipation can be used to measure the irreversibility of heat transfer and entransy loss is

related to the output power for heat-work conversion. Entransy should have relations to the thermodynamic laws. In fact, the second law of thermodynamics has two different expressions and each has its own advantage. If we could express the thermodynamic laws with entransy, it will enrich the theory. In the present work, we attempt to express the three laws of thermodynamics with the concept of entransy, and discuss the application of the expressions.

2. Entransy expression of the first law of thermodynamics

For any thermodynamic cycle, Cheng and Liang [17] obtained

$$T\delta Q = dG + T\delta W, \quad (1)$$

where $T\delta Q$ is named heat entransy flow as it is associated with heat δQ , $T\delta W$ is called work entransy flow as it is associated with work δW , and dG is the entransy change of the working medium [17]. It can be seen that part of the heat entransy flow into the working medium becomes the entransy of the working medium, and the rest is used to do work. This is the entransy balance of the working medium.

For a cycle, the integration of eq. (1) gives [17]

$$\oint T\delta Q = \oint dG + \oint T\delta W = \oint T\delta W = G_W, \quad (2)$$

where G_W is the total work entransy of the cycle. When a cycle is finished, the working medium gets back to the initial state and its entransy will also return to the initial value. It can be seen that all the heat entransy flow into the working medium is consumed in the work doing process.

Considering a common thermodynamic process in Fig. 1, the energy absorbed from the high temperature heat sources by the working medium is Q_H , while that released to the low temperature heat sources is Q_L , and the output work is W . For the system, Cheng and Liang [17] got

$$G_H - G_L - \Delta G - G_W = 0, \quad (3)$$

where G_H is the heat entransy flow from the high temperature heat source, G_L is that into the low temperature heat source, and ΔG is the entransy decrease during heat transfer between the heat sources and the working medium. As ΔG is called entransy dissipation [6,20,21], we have

$$G_H - G_L - G_{dis} - G_W = 0. \quad (4)$$

It can be found that some of the entransy flow from the high temperature heat sources flows into the low temperature heat sources, some is dissipated during the transfer processes between the heat sources and the working medium system, and the rest turns to be the work entransy flow. The entransy of a common

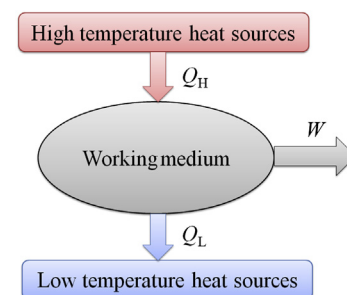


Fig. 1. Sketch of a thermodynamic process.

thermodynamic process is also in balance. This is the entransy expression of the first law of thermodynamics.

3. Entransy expressions of the second law of thermodynamics and the relationship between the expressions

3.1. Entransy expressions of the second law of thermodynamics

For the second law of thermodynamics, Clausius described it with an expression that it is impossible to construct a device that produces no effect other than the transfer of heat from a lower temperature body to a higher temperature body in 1850, while Kelvin introduced another expression based on heat-work conversion, that is, it is impossible for any device to operate in a cycle and receive heat from a single reservoir and produce an equivalent amount of mechanical work in 1851 [44].

For the Clausius expression, when $T_H > T_L$ in the heat transfer process as shown in Fig. 2, there must be

$$\delta Q \leq 0, \quad (5)$$

where δQ is the heat transported from the body with the initial temperature T_L to that with the initial temperature T_H . When the heat transfer process is analyzed from the viewpoint of entransy, it will be found that the entransy of the whole system would never increase whether the internal energies of the bodies are dependent on their temperatures or not [20,45]. Therefore, any heat transfer process leads to

$$\Delta G \leq 0. \quad (6)$$

As the entransy always decreases during heat transfer processes, the decreased entransy is named entransy dissipation, which could be used to describe the irreversibility of heat transfer [6,20,21]. There is

$$G_{\text{dis}} = -\Delta G \geq 0. \quad (7)$$

Based on eqs. (6) and (7), it can be seen that the entransy flow would never be transported from a low temperature body to a high temperature body spontaneously and heat transfer processes would always result in entransy dissipation. This is the entransy expression of the second law of thermodynamics for heat transfer.

For the Kelvin expression, it can also be expressed with the concept of entransy. Assume that a reversible thermodynamic cycle is finished between a single heat source and a heat engine as shown in Fig. 3. In the cycle, Q is the heat absorbed from the single heat source and W is the output work of the heat engine. According to the first law of thermodynamics, there is

$$Q = W. \quad (8)$$

Moreover, the Kelvin expression tells us that the thermodynamic process in Fig. 2 is impossible, so there must be

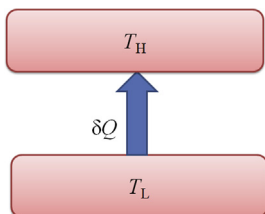


Fig. 2. Sketch of a heat transfer process.

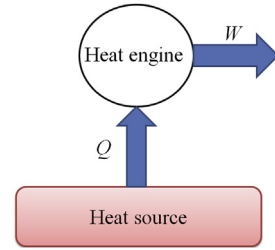


Fig. 3. Heat-conversion between a single heat source and a heat engine.

$$Q = W \leq 0. \quad (9)$$

As the cycle is reversible, eq. (4) can be changed as

$$G_{\text{hs}} - G_W = 0, \quad (10)$$

where G_{hs} is the entransy flow from the single heat source, and G_W is the working entransy of the heat engine. Considering that W is negative and the temperature of the heat engine would always be positive, there is

$$G_{\text{hs}} = G_W = \oint T \delta W \leq 0. \quad (11)$$

Equation (11) tells us that it is impossible for any device to operate in a cycle and receive heat entransy flow from a single reservoir, and result in an equivalent amount of work entransy flow. This is the entransy expression of the second law of thermodynamics in heat-work conversion.

3.2. Relationship between the entransy expressions of the second law of thermodynamics

First, we assume that the entransy expression of the second law of thermodynamics in heat transfer, eq. (6), was not tenable. Then, the thermodynamic process as shown in Fig. 4 is analyzed below. There are two heat sources whose temperatures are T_H and T_L , respectively. Assume that $T_H > T_L$. As eq. (6) was not tenable, one heat engine may produce no effect other than the transfer of entransy flow G_1 from the heat source with temperature T_L to the heat source with temperature T_H . At the same time, we can assume that another reversible heat engine works between the heat sources. The second heat engine absorbs the entransy flow G_1 from the high temperature heat source, releases the entransy flow G_2 to the low temperature heat source, and the entransy flow used to do work is G_W . According to eq. (4), there is

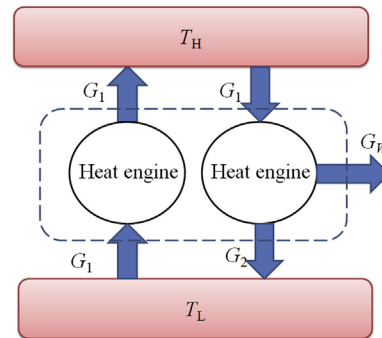


Fig. 4. Sketch of the thermodynamic process when the entransy expression of the second law of thermodynamics in heat transfer was not tenable.

$$G_W = G_1 - G_2. \quad (12)$$

As the second heat engine is reversible, there is

$$\begin{aligned} G_W &= G_1 - G_2 = Q_1 T_H - Q_2 T_L = Q_1 T_H - Q_1 \frac{T_L^2}{T_H} \\ &= Q_1 T_H \left(1 - \frac{T_L^2}{T_H^2} \right) > 0, \end{aligned} \quad (13)$$

where Q_1 and Q_2 are the heat absorbed from the high temperature heat source and that released to the low temperature heat source, respectively.

If we treat the two heat engines as one equipment, it can be found that the entransy flow that this equipment absorbs from the high temperature heat source is zero, that absorbs from the low temperature heat source is $G_1 - G_2$, and the work entransy flow of the equipment is G_W . Therefore, all the work entransy flow comes from the single heat source with temperature T_L . It means that the entransy expression of the second law of thermodynamics in heat-work conversion, eq. (11), was not tenable.

On the other hand, we can also assume that the entransy expression of the second law of thermodynamics in heat-work conversion was not tenable first. In this case, the thermodynamic process shown in Fig. 5 is discussed. In Fig. 5, the temperatures of the high and the low temperature heat sources are also T_H and T_L , respectively. As eq. (11) was not tenable, one reversible heat engine may absorb the heat entransy flow G_1 from the high temperature heat source, and result in an equivalent amount of work entransy flow G_W . At the same time, it could be assumed that the work entransy flow goes into another reversible heat engine, and makes a reverse Carnot cycle work. In the reverse Carnot cycle, the heat engine absorbs the heat entransy flow G_2 from the low temperature heat source and releases the heat entransy flow G_3 to the high temperature heat source. Moreover, considering eq. (4), the net heat entransy flow of the high temperature heat source is

$$G_3 - G_1 = G_3 - G_W = G_2 > 0. \quad (14)$$

If we treat the two heat engines as one equipment, eq. (14) tells us that the equipment absorbs the net heat entransy flow G_2 from the low temperature heat source and releases it into the high temperature heat source. It means that the entransy expression of the second law of thermodynamics in heat transfer was not tenable.

On the whole, the entransy expressions of the second law of thermodynamics are tenable at the same time. Therefore, they are equivalent to each other.

4. Entransy expression of the third law of thermodynamics

The third law of thermodynamics tells us that it is impossible to reach to temperature of 0 K through limited processes. This

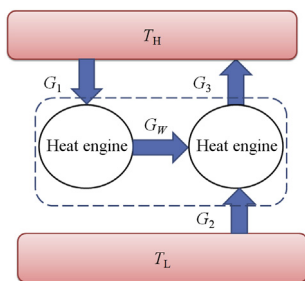


Fig. 5. Sketch of the thermodynamic process when the entransy expression of the second law of thermodynamics in heat-work conversion was not tenable.

law could be proved with the first and second laws of thermodynamics.

First, we assume that 0 K could be achieved. Then, let a Carnot cycle works between an isothermal heat source with temperature T_H ($T_H > 0$ K) and one with 0 K. According to the Carnot theorem, there is

$$\delta W = \delta Q \left(1 - \frac{T_0}{T_H} \right) = \delta Q. \quad (15)$$

where $T_0 = 0$ K, δW is the output work of the cycle, and δQ is the heat absorbed by the working medium from T_H . It can be found that eq. (15) violates the second law of thermodynamics. Therefore, the assumption would not be tenable, and 0 K could not be achieved.

With the concept of entransy, the above law can also be expressed. As the entransy of a body is half of the product of its temperature and internal energy [6,44], it can be found that it is impossible to achieve zero entransy (0 J·K) for any body through limited processes. This is the entransy expression of the third law of thermodynamics, which can also be proved by the entransy expressions of the first and second laws of thermodynamics. Firstly, we also assume that the zero entransy 0 (J·K) could be achieved for a body. Then, when a Carnot cycle works between the body with zero entransy and an isothermal heat source with temperature T_H ($T_H > 0$ K), combining eqs. (2) and (15) gives

$$\delta G_W = T_H \delta Q - (\delta Q - W) T_0 = T_H \delta Q = \delta G_Q. \quad (16)$$

It can be seen that eq. (16) violates the entransy expression of the second law of thermodynamics for heat-work conversion. Therefore, zero entransy cannot be achieved.

5. Proof of the Clausius inequality with the entransy expressions of the thermodynamic laws

Based on the entransy expressions of the thermodynamic laws, the Clausius inequality could be proved as following.

As shown in Fig. 6, the reversible thermodynamic cycle has n heat sources. The temperature of the i th heat source is T_i . The system (SYS) comes into contact with each heat source in turn. Finally, it returns to the first source and the cycle is completed.

Assume that SYS absorbs heat entransy flow G_i from the i th heat source and its work entransy flow is G_W . According to entransy expression of the first law of thermodynamics, there is

$$\sum_{i=1}^n G_i = G_W. \quad (17)$$

We consider an auxiliary heat source whose temperature is T_0 , and n Carnot engines working between the heat sources and the

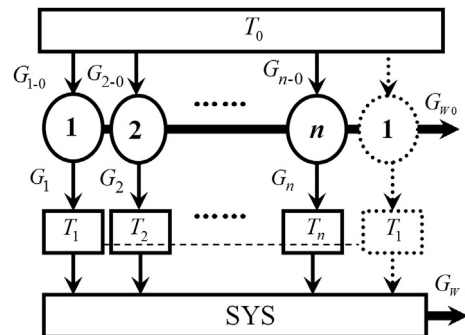


Fig. 6. Sketch of a reversible thermodynamic cycle with n heat sources.

auxiliary heat source. We assume that the i th engine receives heat entransy flow G_{i-0} from the auxiliary heat source, and the heat entransy flow that the i th heat source obtains from the i th engine is equal to the heat entransy flow that SYS receives from the i th heat source. According to the first law of thermodynamics, the work entransy flow of all the engines is

$$G_{W0} = \sum_{i=1}^n G_{i-0} - \sum_{i=1}^n G_i. \quad (18)$$

Therefore, we could obtain

$$G_{W0} + G_W = \sum_{i=1}^n G_{i-0}. \quad (19)$$

If SYS and all the Carnot engines are treated as a large system, then the total system finishes its cycle while SYS and the Carnot engines finish their cycles. The term on the right-hand side of eq. (19) is then the heat entransy flow that the total system receives only from the auxiliary heat source. Considering the entransy expression of the second law of thermodynamics in heat-work conversion, we could get that

$$G_{W0} + G_W = \sum_{i=1}^n G_{i-0} \leq 0. \quad (20)$$

For the Carnot engines, there is [44]

$$\frac{Q_{i-0}}{Q_i} = \frac{T_0}{T_i}, \quad (21)$$

where Q_{i-0} is the heat that the i th Carnot engine absorbs from the auxiliary heat source, and Q_i is that the engine releases to the i th heat source. Considering eqs. (20) and (21), there is

$$\sum_{i=1}^n G_{i-0} = \sum_{i=1}^n (Q_{i-0} T_0) = \sum_{i=1}^n \left(T_0^2 \frac{Q_i}{T_i} \right) = T_0^2 \sum_{i=1}^n \left(\frac{Q_i}{T_i} \right) \leq 0. \quad (22)$$

Then, there is

$$\sum_{i=1}^n \left(\frac{Q_i}{T_i} \right) \leq 0. \quad (23)$$

If the number of heat sources is infinite, and the temperature differences of the adjacent heat sources are infinitesimal, eq. (23) can be rewritten as

$$\oint \frac{\delta Q}{T} \leq 0. \quad (24)$$

This is the Clausius inequality [44]. The equal sign in eq. (24) is tenable only when the process is reversible while the sign of “less than” is tenable for any irreversible process. eq. (24) is just the basis of the definition of entropy [44].

6. Entransy loss and its applications

In eq. (4), the heat entransy flow G_H is absorbed from the heat sources by the working medium in a cycle, while only the heat entransy flow G_L is released to the heat sources. Therefore, the entransy loss of the heat sources is [17–19]

$$G_{\text{loss}} = G_H - G_L = G_{\text{dis}} + G_W. \quad (25)$$

In heat transfer, the work entransy flow is zero because there is no output work. The entransy loss in heat transfer is the entransy dissipation. There is

$$G_{\text{loss}} = G_{\text{dis}}. \quad (26)$$

With the concept of entransy dissipation, the EEDP and the MTRP were developed [6], which are proved to have better suitability for heat transfer optimization than the entropy generation minimization [1,2,6,24,25,31,32,34,37–40].

For heat-work conversion, let us discuss the relationship between the maximum entransy loss and exergy for a thermodynamic system first. Assume that there is a system with temperature T and internal energy U , and its heat capacity is infinite. If we assume that a Carnot engine works between the system and the environment with temperature T_0 , the exergy in the system is

$$E = U(1 - T_0/T). \quad (27)$$

If Q_0 is the minimum heat flow into the environment, the maximum entransy loss in the body can be expressed as

$$G_{\text{loss-max}} = UT - Q_0 T_0 = UT \left[1 - (T_0/T)^2 \right]. \quad (28)$$

It can be seen that the increase in U and T leads to the increase in exergy and maximum entransy loss of the system at the same time. When the heat capacity of the system is finite, Cheng and Liang [46] proved that both the exergy and the maximum entransy loss of the system will increase with increasing U and T . On the other hand, there is no entropy generation in the above cases.

As below, we discuss the applications of entransy loss in some thermodynamic cycles. When the heat-work conversion process is reversible, combining eqs. (4) and (26) leads to

$$G_{\text{loss}} = G_W. \quad (29)$$

Considering the Carnot cycle, we can get [17]

$$G_{\text{loss}} = G_W = Q_H T_H - Q_L T_L = Q_H T_H \left[1 - (T_L/T_H)^2 \right], \quad (30)$$

where Q_H and Q_L are the heat absorbed by the working medium from the high temperature heat source with temperature T_H and that released to the low temperature heat source with temperature T_L , respectively. The output work of the Carnot cycle is

$$W = Q_H (1 - T_L/T_H). \quad (31)$$

It can be found that the entransy loss and the output work both increase with increasing T_H and Q_H or decreasing T_L . However, the entropy generation of the reversible cycle is always zero.

From the above cases, it can be found that the concept of entropy generation cannot always describe the change in exergy for thermodynamic systems, while the concept of entransy loss can.

For a common closed thermodynamic system, the entransy loss rate is [41]

$$\dot{G}_{\text{loss}} = \int_A q T dA + \int_V Q_V T dV, \quad (32)$$

where q is the heat flux density, A is the surface area of the system, V is the volume, and Q_V is the inner heat source. For the system shown in Fig. 1, assume that there are n high temperature heat sources, m low temperature heat sources and no inner heat source. The working medium absorbs Q_{H-i} from the i th high temperature heat source with temperature T_{H-i} , and releases Q_{L-j} to the j th low temperature heat source with temperature T_{L-j} . Then, eq. (32) can be rewritten as

$$\dot{G}_{\text{loss}} = Q_H T_{H-\text{in}} - Q_L T_{L-\text{out}}, \quad (33)$$

where $T_{H-\text{in}}$ and $T_{L-\text{out}}$ are the equivalent temperatures of the high and low temperature heat sources,

$$T_{H-in} = \sum_{i=1}^n Q_{H-i} T_{H-i} / Q_H, T_{L-out} = \sum_{j=1}^m Q_{L-j} T_{L-j} / Q_L. \quad (34)$$

Considering the energy conservation leads to

$$\dot{G}_{loss} = Q_H(T_{H-in} - T_{L-out}) + W T_{L-out}. \quad (35)$$

It can be seen that larger entransy loss corresponds to larger output work when the input heat of the system and the equivalent temperatures of the high and low temperature heat sources are prescribed. Some researches verified eq. (35) and showed that smaller entropy generation rate does not always lead to larger output power [17–19,41,42].

7. Conclusions

In this paper, the entransy expressions of the three laws of thermodynamics are discussed. The entransy expression of the first thermodynamic law states that the entransy of any thermodynamic system is in balance. The entransy expression of the second thermodynamic law for heat transfer indicates that the entransy flow will never be transported from a low temperature body to a high temperature body automatically and heat transfer processes will always result in entransy dissipation. The expression of the second thermodynamic law for heat-work conversion is that it is impossible for any device to operate in a cycle and receive heat entransy flow from a single reservoir, and result in an equivalent amount of work entransy flow. The two entransy expressions of the second law of thermodynamics are proved to be equivalent to each other. The entransy expression for the third law of thermodynamics points out that it is impossible to achieve zero entransy for any body through limited processes. In addition, the third law is proved based on the first and second laws.

With the entransy expressions of thermodynamics, the Clausius inequality is proved. Entransy loss of thermodynamic processes is defined and found to be applicable for the analyses and optimizations of heat transfer and heat-work conversion processes.

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